Freezing-resistant liquid water in porous media, a possible mechanism to account for the fluidized transport of sediments on Mars: an example from East Gorgonum crater

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ABSTRACT

A mudflow-like deposit resting on the bottom of the East Gorgonum Crater (Mars; 37.4°S, 168.0°W) may provide new insight regarding the debate on the existence of water over the Martian surface. Because water in a mudflow is confined to a porous medium, we analyse this case from the perspective of non-equilibrium systems. Fluids confined to porous media behave in a special way, the system being ruled by kinetic restrictions, which alter the expected thermodynamic equilibrium. These non-equilibrium conditions allow the existence of pure liquid water to temperatures as low as − 40 °C, and even less if the system includes brines. Thus, application of the triple point diagram of water on the Martian surface may constitute a simplistic approach if we are dealing with confined, and yet moving, water in the form of a mudflow. We further suggest that the V-shaped channels excavated alongside the mudflow may have been caused by water rejected by syneresis from the moving sediment. We finally indicate that the series of deeply entrenched channels and debris aprons that occur only in the northern half of the crater might be related to the regional slope, which decreases in altitude to the south.

Introduction

The debate on the existence of water on Mars has lasted for many years. Contrary to what might have been foreseen, the arrival of high-resolution images from the Mars Global Surveyor has merely stirred the debate further (e.g. Hoffman, 2000; Malin and Edget, 2000, among others). Several papers strongly suggest the existence of water beneath the Martian surface (e.g. Malin and Edget, 2000; Baker, 2001; Costard *et al.*, 2001, 2002; Hartmann, 2001; Jakosky and Phillips, 2001; Mellon and Phillips, 2001; Gilmore and Phillips, 2002; Knauth and Burt, 2002; Christensen, 2003, among others). This idea is supported by geomorphic features on Martian impact craters, south polar pits and valleys indicating groundwater seepage and surface runoff. In contrast, Hoffman (2000) proposes that many of these geomorphic features may have been originated by flows generated by the extensional collapse of unstable rock masses at the foot of cliffs, closely resembling volcanic avalanches. In fact the analogy goes further, because Hoffman (2000) suggests that these flows would be akin to terrestrial gas-supported pyroclastic flows such as ignimbrites or surges, only at very low temperatures, with CO_2 as the main gaseous phase.

We here discuss an elongated sedimentary deposit in East Gorgonum Crater on Mars (37.4°S, 168.0°W) (Fig. 1) resembling in many aspects a terrestrial mudflow-type deposit (Fig. 2), which strongly suggests that liquid water may be, or may have been, present in Gorgonum. We suggest a possible mechanism to account for the integrity of liquid water within a moving fluidized sediment despite restrictive external *P–T* conditions.

Mudflow deposits in East Gorgonum crater: thermodynamic considerations

Mudflows are common in arid and semi-arid regions that receive short but intense rainstorms (Fig. 2). Snow melting may provide an additional source of saturation water. These factors convert the regolith into a mass of viscous mud that can move downslope at high velocity. Mudflows (or muddy debris flows) are considered a type of gravity mass flows characterized by non-Newtonian viscoplastic rheology, for which the whole sediment concentration by volume is 50–90% (note that not much water is involved in large mobilized volumes) with a fine fraction above 10% (e.g. Coussot and Meunier, 1996). Thus, mudflows are flows of transient nature, comprising a mixture of liquid water – solid matter in which both components move in unison, in most cases under a laminar regime. The high volumetric sediment concentration distinguishes mudflows and debris flows from natural Newtonian flows (such as 'normal' density currents and water two-phase floods) which normally have a volumetric sediment content below 25%. Mudflows and debris flows must be considered as materials that undergo changes of state. They originate from nearly rigid state, move fluidly and eventually form deposits in a nearly rigid state. Mudflows may have a Newtonian hyperconcentrated flow tail when the solid concentration becomes smaller than a critical value, which may be caused by water/sediment availability during the flow. Thus, most shear resistance in debris flows is generated by Coulomb friction [$\tau = \sigma(\tan\varphi_s)$, where τ represents bulk intergranular

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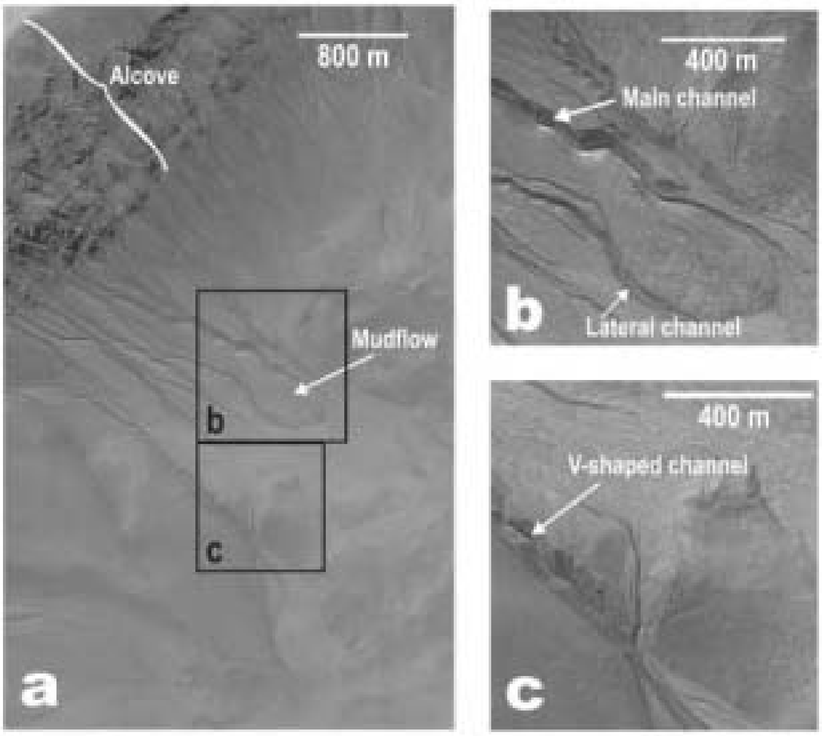

Fig. 1 Northern sector of the East Gorgonum crater. Note the head alcove (a), representing a source morphology (Malin and Edget, 2000); detail of a mudflow-like deposit (b); and a V-shaped channel (c). MOC images M0701873, M1401830, M1501466; see also MGS MOC Release No. MOC2-241.

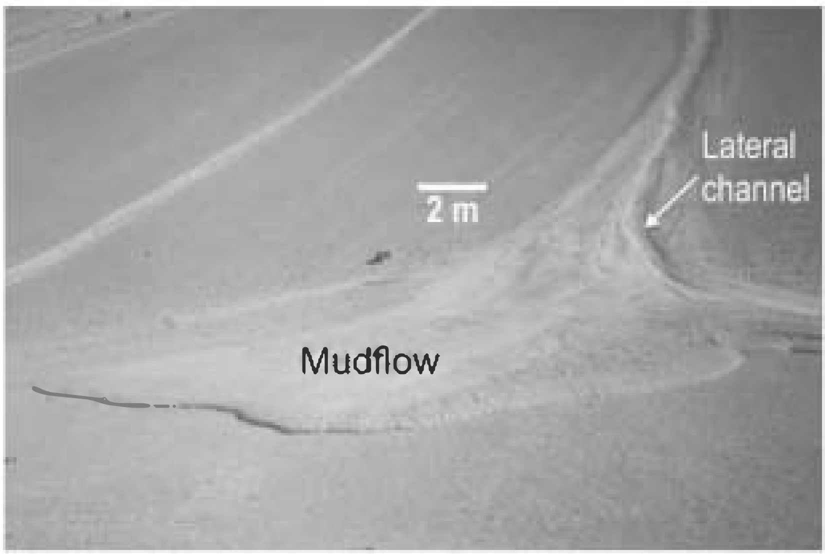

Fig. 2 Recent mudflow in the Atacama desert (northern Chile). Road from Copiapó to Maricunga (2300 m above sea level). Note the associated lateral channel on the right.

shear stress, σ intergranular normal stress and φ_s the static frictional angle].

A close inspection of images from the 12-km-wide East Gorgonum Crater crater (Fig. 1a) reveals a series of deeply entrenched channels, debris aprons (Malin Space Systems, 2001) and a well-documented ~ 2-km-long, 350-m-wide (maximum), front-lobed geomorphic feature that closely resembls a terrestrial mudflow deposit (Fig. 1a,b). We are aware of the many thermodynamic considerations ruling out the existence of liquid water on the surface of Mars (e.g. Hoffman, 2000, among others). For example, the extremely low pressures in the region of Gorgonum (4.5 5.5 mbar; Nasa Ames Mars General Circulation Model, 2002) are below that of the water triple point (~ 6.1 mbar). Thus, although the highest temperatures in this zone may reach up to 290 K (Nasa Ames Mars General Circulation Model, 2002), pressure constraints only allow a phase change from solid to gas. However, in the Gorgonum case we would not be dealing with a typical case of on-surface-free-water, but with water confined to a porous material (i.e. a mudflow). This makes a considerable difference because under such conditions the classic thermodynamic approach (phase diagram for water) may not apply. For example, as early as the 1960s it was recognized that classic thermodynamics was of limited use for many soil water interactions (Takagi, 1966), and that the amount of unfrozen water below 0 °C was, among other factors, related to the particle size of the sediment, i.e. the finer the sediment, the greater the amount of unfrozen water (Nerseova and Tsytovich, 1966). Modern studies have shown that liquid water can be found in soils and other porous media at temperatures as low as − 40 °C, i.e. well below the bulk melting temperatures (Cahn *et al.*, 1992; Maruyama *et al.*, 1992, among others) or even at − 80 °C in the interstices of shallow hypersline soils in the Antarctic cold deserts, a plausible equivalent to Martian environmental conditions (Wynn-Williams *et al.*, 2001). The process has been also studied by Landis (2001), who relates the lowering of the freezing point to capillary-pore effects (− 63 °C). Although soils do freeze (e.g. permafrosts in cold regions), the process is not necessarily complete, and a good example is provided by the so-called taliks, i.e. localized unfrozen layers located underneath or within masses of permafrost (Arcone, 2001;

Pidwirny, 2002). Taliks occur below rivers and lakes, where strong springs emerge, or can be totally detached from the surface, surrounded by permafrost (closed taliks; Pidwirny, 2002). This hydrological feature may be particularly relevant to the Gorgonum case, because as Costard *et al.* (2001) have noted, the most spectacular erosion landforms on Mars occur precisely at the intersection between crater rims and wrinkle ridges, which display similar characteristics to taliks observed in Siberia, suggesting that these Martian features may represent perched taliks. Furthermore, Andersen *et al.* (2002) relate the existence of cold springs (+ 6 °C; low-temperature brines) in permafrost from the Canadian High Artic (Axel Heiberg Island; mean annual temperature of − 15 °C) to possible equivalent scenarios on Mars.

An alternative view: non-equilibrium systems

The concept of hysteresis basically refers to a retardation of the effect when forces acting upon a body are changed. In the case of liquids, the hysteresis freezing temperature, as opposed to the thermodynamic freezing temperature, is defined as the limit of metastability of the liquid phase during freezing (Radhakrishnan *et al.*, 2000). Cooling runs on water in porous materials show still pure liquid at − 29 °C. An abrupt change from liquid to solid is observed at − 31 °C, whereas a complete transformation to the solid phase occurs at − 45 °C (Morishigue and Kawano, 1999). Liquids can be supercooled below the thermodynamic freezing transition because of the presence of a kinetic barrier to crystallization (Morishigue and Kawano, 1999). This phenomenon is particularly important in small, completely confined spaces where kinetic energy is substantially reduced. In other words, the freezing temperature, as compared to the bulk temperature, can be severely depressed in confined spaces, i.e. porous media (Radhakrishnan *et al.*, 2000):

$$\Delta T_{\mathrm{m}} = T_{\mathrm{m.pore}} - T_{\mathrm{m.bulk}} < 0$$

where T_{m} is the temperature of melting, $T_{\mathrm{m.pore}}$ is the temperature of melting in the pores and $T_{\mathrm{m.bulk}}$ is the temperature of melting in the bulk, thus allowing the existence of liquid water up to extremely low temperatures (Cahn *et al.*, 1992; Maruyama *et al.*, 1992; Morishigue and Kawano, 1999; Radhakrishnan *et al.*, 2000, among others). In turn, the depression of T_{m} is proportional to H^{-1} (where H is the pore width) as predicted by the Gibbs–Thompson equation (Sliwinska-Bartkowiak *et al.*, 1999).

If dissolved salts are present (e.g. as is probable on Mars; Wynn-Williams *et al.* 2001; Knauth and Burt, 2002), these effects can be enhanced by two mechanisms: (a) further depression of the freezing point, controlled by the concentration and nature of salts in solution (e.g. about − 56 °C for the H_2O–NaCl–KCl–$CaCl_2$ system; Konnerup-Madsen, 1979); and (b) salt rejection, because pure water tends to freeze at a freezing front, leaving a progressively more concentrated solution (and therefore with an even more depressed freezing point) (e.g. Parameswaran and Mackay, 1996). Additionally, as noted by Dickinson and Rosen (2003), a variety of brine solutions can maintain an aqueous phase to − 50 °C, which is well within the range of summer surface temperatures on Mars.

The pressure governing the liquid–solid system in the Martian case under study is the internal pressure (P_{int}) within the mudflow, and not the atmospheric pressure acting on the surface of the planet. Given the extremely low values of the atmospheric pressure (P_{atmos}) on the Martian surface, then $P_{\mathrm{int}} > P_{\mathrm{atmos}}$, which will further increase stability of the liquid phase. For example, given a mudflow thickness of 10 m (a reasonable estimate for a 2-km-long deposit), a point in the middle of the flow would be subjected internal pressures of about 1470 g cm^{-2} (sediment – liquid water 1 : 1; $G_{\mathrm{Mars}} = G_{\mathrm{earth}} \times 0.375$), i.e. the equivalent to ~ 1440 mbar.

One may argue that metastable water would freeze under a noticeable strain, such as the movement of a mudflow (metastability breaking); however, although this may be a reasonable argument in the case of free (bulk) water, it can hardly apply to the case under consideration. Given that: (1) viscosity has an exponential dependence on temperature (e.g. Murrel and Jenkins, 1994); (2) we are dealing with a very low-temperature fluid (confined to a porous medium), and therefore of higher viscosity; and (3) metastibility of a fluid phase depends (among other factors) on viscosity, i.e. the higher the viscosity the harder to break metastability, it follows that we may expect the integrity of a mudflow to be maintained, at least for a short distance, as shown by the example of Gorgonum crater.

Thus we suggest that the metastable behaviour of water in a porous material (coupled with the effective pressure within the sediment: P_{int}, and high salinity) offers an alternative and plausible explanation for the stability of liquid water, thus opening new perspectives for understanding sediment transport under fluidized conditions on the Martian surface. We further suggest that the physics of non-equilibrium systems may also provide an alternative or complementary approach for understanding taliks on Earth.

Other related phenomena in East Gorgonum Crater

We suggest that the origin of the deeply entrenched channels bounding the Gorgonum mudflow deposit (Fig. 1b,c) may be related to syneresis-type phenomena (separation of a liquid from a gel; or in this case, from a fluidized sediment). If, as expected, a mudflow laterally leaks water during movement, then lateral water-excavated channels may form (Fig. 2). In turn, this water may both promote rapid erosion and sediment transport of fine unconsolidated sediments. In the Gorgonum case the erosion channels are not much longer than the associated mudflow (Fig. 1b,c), which indicates that channel-forming processes may have been related to lateral water segregation from the fluidized sediment (see also Fig. 2 for comparison). Furthermore, if the rejected liquid is a brine (e.g. Wynn-Williams *et al.*, 2001), then we would expect a lower freezing point and higher boiling point. Because liquid water would rapidly evaporate (in this case P_{atmos} controls the system) it is clear that this phenomenon is highly transient. However, given that a phase change from liquid to gas would not be instantaneous for the total amount of rejected

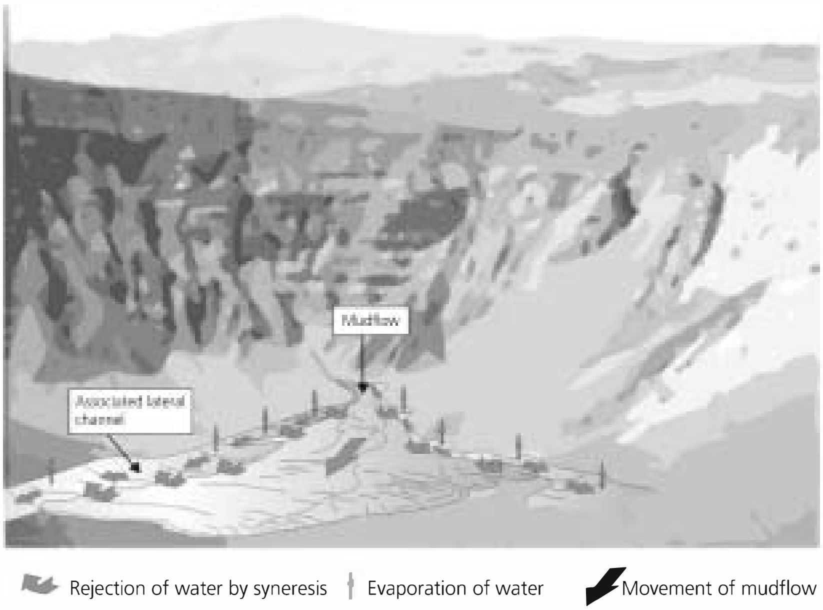

Fig. 3 Simplified model for East Gorgonum type mudflows on Mars. Note the associated lateral channels (compare with Fig. 2) that may be excavated by water rejected by syneresis.

water, part of it would remain as such during the downslope movement of the mudflow. Moreover, as the mudflow advances, more liquid water would be laterally rejected and added to the system as a result of syneresis (Fig. 3). The steeper the slope (as in Gorgonum) (Fig. 1a), the higher the energy of the running water, and therefore, the deeper the trenches (V-type channels) that can be excavated in the unconsolidated sediments (Fig. 1b,c).

Finally, inspection of the crater image (Fig. 1a) shows that the series of deeply entrenched channels and debris aprons occur only in the northern half of the crater. Malin and Edget (2000) suggest that this is due to climatic and geographical factors. An alternative explanation for this asymmetrical phenomenon might be related to the regional slope, which decreases in altitude to the south. If groundwater exists within a specific regional stratigraphic horizon, this should leak along the northern face of basins and/or craters, following the regional slope (Fig. 4), which is also observed in the northern faces of canyons in the so-called Gorgonum Chaos, some 100 km to the west of the crater (Malin Space Systems, 2001).

Conclusions

The physics of non-equilibrium systems offers an alternative view regarding the debate on the existence of liquid water over the Martian surface. We provide theoretical evidence suggesting that liquid water can defy thermodynamics rules, providing that it is confined to porous media (as we would expect within a mudflow). Kinetic restrictions during phase changes of water (and not equilibrium temperatures) need to be taken into account. The process can be enhanced if dissolved salts are present. Internal

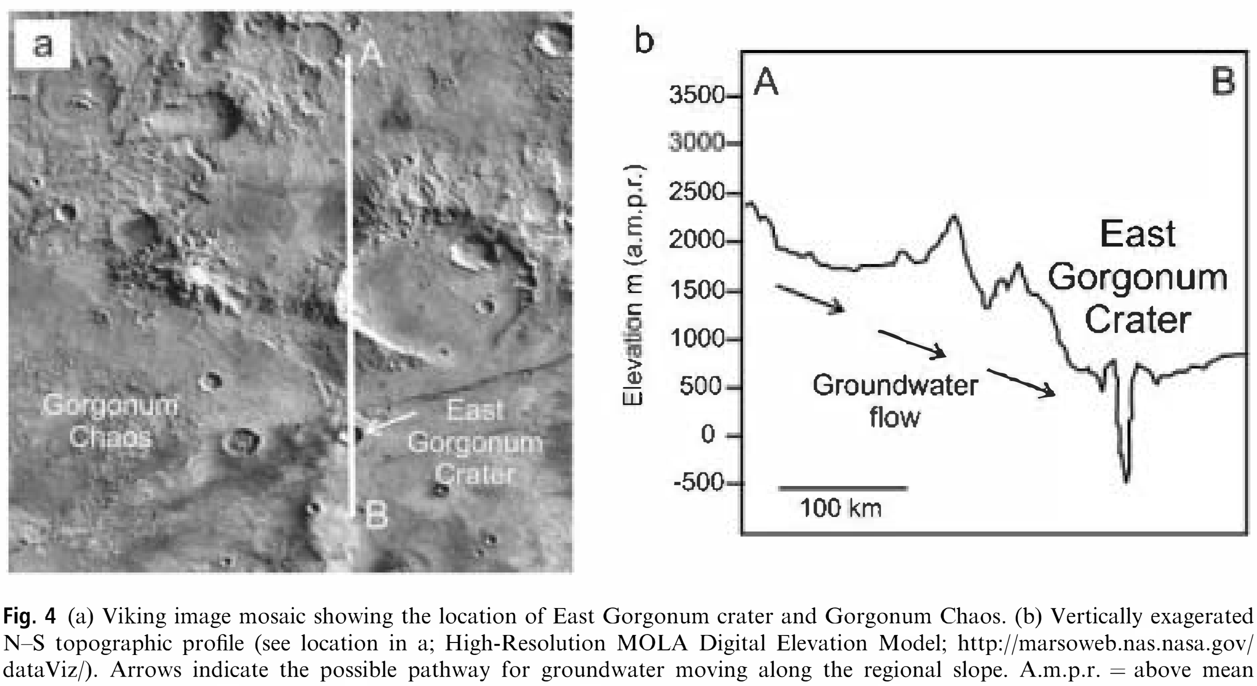

Fig. 4 (a) Viking image mosaic showing the location of East Gorgonum crater and Gorgonum Chaos. (b) Vertically exagerated N–S topographic profile (see location in a; High-Resolution MOLA Digital Elevation Model; http://marsoweb.nas.nasa.gov/dataViz/). Arrows indicate the possible pathway for groundwater moving along the regional slope. A.m.p.r. = above mean planetary radius.

pressure within the flow, and not that acting on the Martian surface, needs to be considered. The non-equilibrium conditions met within a downslope moving mudflow provide a plausible environment to allow liquid water displacement on the Martian surface (Fig. 3). Furthermore, although we may be describing a highly transient phenomenon, water rejection from the mudflow due to syneresis-type phenomena provides an alternative mechanism to account for the deeply entrenched channels flanking mudflow deposits on the Martian surface (Figs 1a–c and 3).

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